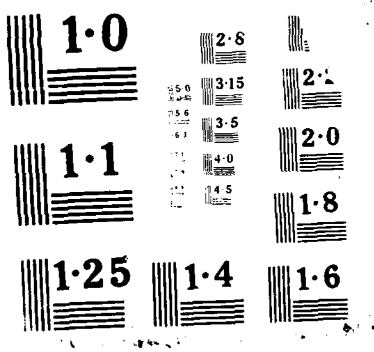
ON FRACTURE AT HIGH (U) SRI INTERNATIONAL MENLO PARK
CA J H GIOVANOLA ET AL 03 MAR 88 AFOSR-TR-88-0291
UNCLASSIFIED F49620-86-K-0010 F/G 11/6.1 NL


1·0
2·8
3·15
2·0
3·5
4·0
1·1
4·5
1·8
1·25
1·4
1·6

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

DTIC FILE COPY (2)

REPORT DOCUMENTATION PAGE

AD-A192 957

1b. RESTRICTIVE MARKINGS	
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	3. DISTRIBUTION / AVAILABILITY OF REPORT
4. PERFORMING ORGANIZATION REPORT NUMBER(S) PYU-1750	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 88-0
6a. NAME OF PERFORMING ORGANIZATION SRI International	6b. OFFICE SYMBOL (If applicable)
7a. NAME OF MONITORING ORGANIZATION Air Force Office of Scientific Research	
6c. ADDRESS (City, State, and ZIP Code) 333 Ravenswood Avenue Menlo Park, CA 94025	7b. ADDRESS (City, State, and ZIP Code) Bolling Air Force Base Washington, DC 20332
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Same as 7a	8b. OFFICE SYMBOL (If applicable)
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER ~~AFOSR~~ F49620-86-K-0018	
8c. ADDRESS (City, State, and ZIP Code) Same as 7B	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO 61102F; PROJECT NO 2306; TASK NO A1; WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)
INFLUENCE OF MICROSTRUCTURE AND MICRODAMAGE PROCESSES ON FRACTURE AT HIGH LOADING RATES

12. PERSONAL AUTHOR(S)
J. H. Giovanola and D. A. Shockey

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Annual	FROM 870201 TO 880131	880303	19

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Ti-10V-2Fe-3Al, microstructure, dynamic fracture, initiation toughness, propagation toughness
20	11		
11	06		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The optimal use of advanced beta and near-beta titanium alloys in situations involving dynamic or shock loading requires an understanding of the influence of microstructure and loading rate on fracture behavior

To address this need, SRI is performing dynamic crack initiation and propagation experiments on Ti-10V-2Fe-3Al in three microstructural conditions, varying the loading rate to establish the rate-dependence of the fracture toughness. A new experimental method developed in a previous Air Force Office of Scientific Research program

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclass
22a. NAME OF RESPONSIBLE INDIVIDUAL Rosenstein	22b. TELEPHONE (Include Area Code) (202) 767-4933 — 22c. OFFICE SYMBOL NE

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

#19 - ABSTRACT (Continued)

(the one-point-bend impact test) and numerical simulations of the experiments are used to determine dynamic initiation and propagation toughness. Further, the fracture surface topography analysis (FRASTA) technique is applied to the fractured specimens to elucidate the microstructural failure mechanisms controlling fracture in each of the investigated microstructures. The FRASTA results will be used to develop a model capable of explaining the observed fracture behavior. The results of this program will provide guidelines for selecting processing parameters for Ti-10V-2Fe-3Al to optimize strength and toughness.

This report summarizes the progress made during the second year of the program. We performed crack initiation and crack propagation experiments for equally strong microstructures with 0%, 12%, and 40% primary alpha to establish the dependence of initiation and propagation toughness on loading rate and crack speed.

For each microstructure, we found that the initiation toughness increases by 8% to 12% with increasing loading rate. At a given loading rate, the initiation toughness of the 0% primary alpha microstructure was about 6% to 10% lower than the toughness of the two other microstructures. Similarly, a preliminary analysis of the crack propagation experiments indicates that propagation toughness decreases with decreasing primary alpha content. This effect appears to be much larger than the effect on initiation toughness, but it has not yet been quantified.

Scanning electron microscope observations show that for a given loading rate the fracture mode shifts from transgranular to intergranular as the primary alpha content is decreased. We also observed that for a given microstructure the fracture surface roughness decreases with increasing loading rate.

In the next months we will analyze the crack propagation experiments using finite element simulations to obtain the propagation toughness as a function of crack speed. We will continue the FRASTA analysis to correlate the observed fracture behavior with microscopic failure processes and with microstructure.

SRI International

March 1988

AFOSR-TR- 88-0 [illegible]

SRI International
Second Annual Report

INFLUENCE OF MICROSTRUCTURE AND MICRODAMAGE PROCESSES ON FRACTURE AT HIGH LOADING RATES

By: J. H. Giovanola and D. A. Shockey
Principal Investigators
(415) 859-3252/859-2587

With contributions from: R. W. Klopp

Prepared for:

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
AFOSR/NE, Bldg. 410
Bolling Air Force Base
Washington, DC 20332

Attn: Dr. Alan Rosenstein

Contract AFOSR/F49620-86-K-0010DEF
SRI International Project No. PYU-1750

Approved:

G. R. Abrahamson
Vice President
Physical Sciences Division

SRI International

88 3 23 179

CONTENTS

SUMMARY

The optimal use of advanced beta and near-beta titanium alloys in situations involving dynamic or shock loading requires an understanding of the influence of microstructure and loading rate on fracture behavior.

To address this need, SRI is performing dynamic crack initiation and propagation experiments on Ti-10V-2Fe-3Al in three microstructural conditions, varying the loading rate to establish the rate-dependence of the fracture toughness. A new experimental method developed in a previous Air Force Office of Scientific Research program (the one-point-bend impact test) and numerical simulations of the experiments are used to determine dynamic initiation and propagation toughness. Further, the fracture surface topography analysis (FRASTA) technique is applied to the fractured specimens to elucidate the microstructural failure mechanisms controlling fracture in each of the investigated microstructures. The FRASTA results will be used to develop a model capable of explaining the observed fracture behavior. The results of this program will provide guidelines for selecting processing parameters for Ti-10V-2Fe-3Al to optimize strength and toughness.

This report summarizes the progress made during the second year of the program. We performed crack initiation and crack propagation experiments for equally strong microstructures with 0%, 12%, and 40% primary alpha to establish the dependence of initiation and propagation toughness on loading rate and crack speed.

For each microstructure, we found that the initiation toughness increases by 8% to 12% with increasing loading rate. At a given loading rate, the initiation toughness of the 0% primary alpha microstructure was about 6% to 10% lower than the toughness of the two other microstructures. Similarly, a preliminary analysis of the crack propagation experiments indicates that propagation toughness decreases with decreasing primary alpha content. This effect appears to be much larger than the effect on initiation toughness, but it has not yet been quantified.

Scanning electron microscope observations show that for a given loading rate the fracture mode shifts from transgranular to intergranular as the primary alpha content is decreased. We also observed that for a given microstructure the fracture surface roughness decreases with increasing loading rate.

In the next months we will analyze the crack propagation experiments using finite element simulations to obtain the propagation toughness as a function of crack speed. We will continue the FRASTA analysis to correlate the observed fracture behavior with microscopic failure processes and with microstructure.

II INTRODUCTION

The U.S. Air Force is making a considerable effort to develop new weapons systems that perform better, are less costly to produce and maintain, and have increased survivability. One key to achieving these goals is the introduction of new advanced materials in Air Force structures.

Because of their attractive strength-to-weight ratio and good formability, advanced beta and near-beta titanium alloys are finding increasing use in aircraft structural components. These alloys are often used in fracture critical applications, in which they are subjected to dynamic loads. Landing gear parts and wing frame parts are typical examples of applications involving dynamic and shock loads.

Therefore, understanding the dependence of the fracture toughness on loading rate is an important aspect in evaluating advanced titanium alloys for specific applications. Moreover, because of the large variety of microstructures that can be produced from the same alloy composition, an understanding of how microstructure influences fracture behavior is of great importance for the efficient use of these alloys.

The research being conducted at SRI International addresses these needs by investigating the dependence on loading rate and microstructure of the fracture behavior of a promising advanced titanium alloy, Ti-10V-2Fe-3Al. This annual report reviews the specific objectives of the program and summarizes the progress during the second research year.

II OBJECTIVES AND APPROACH

Objectives

To establish how loading rate and microstructure influence the fracture behavior in advanced titanium alloys, we are conducting a 3-year research program with the following specific objectives:

(1) Establish the variation of the initiation toughness K_{Id} with loading rate, and the variation of the propagation toughness K_{ID} with crack speed for a family of Ti-10V-2Fe-3Al microstructures.

(2) Characterize the micromechanisms of failure for each investigated microstructure, loading rate, and crack speed; determine the microstructural parameters that control these mechanisms; and obtain independent, microstructurally based toughness estimates using local crack opening displacement and fracture surface roughness measurements.

(3) Develop a model of dynamic fracture incorporating the influence of microstructure on microdamage processes, and explain the observed behavior of the toughnesses K_{Id} and K_{ID} with changes in microstructure, loading rate, and crack velocity in terms of this model.

Approach

To achieve the program objectives, we are applying advanced experimental methods developed in a previous AFOSR program[1], and a new fractographic technique for deducing microfailure activity from fracture surfaces to determine the behavior of Ti-10V-2Fe-3Al alloy in several microstructural conditions. To characterize the dynamic fracture behavior in terms of continuum fracture mechanics parameters (such as the stress

---

[1] Giovanola, J. H. and Shockey, D. A., "Dynamic Fracture Behavior of Structural Materials," Final Report Prepared for AFOSR, Contract AFOSR/F49620-81-K-0007, SRI International, Menlo Park, CA, July 1986.

intensity factor), we are conducting crack initiation and propagation experiments at several loading rates using the impact one-point-bend test. In selected cases, we are also performing numerical simulations of the experiments. We apply the fracture surface topographic analysis (FRASTA) technique to the fractured specimens to obtain the crack opening displacement directly from microscopic measurements.

The FRASTA technique also allows us to establish which microstructural features control the nucleation, growth, and coalescence of microcracks or microvoids that ultimately lead to macroscopic crack extension. By correlating fractographic observations with toughness measurements (in terms of stress intensity and crack opening displacement), we can determine and model how microstructure and microdamage processes affect fracture at high strain rates. These observations are expected to provide guidance in selecting the optimal microstructure for the Ti-10V-2Fe-3Al system. By comparing the toughness results derived from continuum measurements (stress intensity factor) and from fracture surface observations (crack opening displacement), we can also determine if the concept of stress intensity factor is still valid for fracture at very high loading rates or if new or modified fracture criteria have to be introduced.

III PROGRESS

During the second year of the program, we performed fracture experiments on three different microstructures of Ti-10V-2Fe-3Al. For each microstructure, we established the dependence of the initiation fracture toughness on the loading rate and we established the crack propagation behavior for several initiation conditions. We also made detailed scanning electron microscope observations of fracture specimens from each microstructure and initiated the topographic analysis of selected surfaces. Results of these various tasks are discussed in this section.

Crack Initiation Fracture Experiments

We have performed quasi-static and dynamic crack initiation fracture experiments on the three microstructures selected for the program: 0% primary alpha, 12% primary alpha and 40% primary alpha.

Notched specimen bars were tested in three-point-bending according to ASTM Standard E399 at a loading rate of 0.2 $MPa\sqrt{m}/s$ to obtain the static initiation fracture toughness. Dynamic fracture experiments were performed using the impact one-point-bend test configuration. For these latter experiments, the loading rates varied between 1.1×10^6 and 1.4×10^6 $MPa\sqrt{m}/s$. The results of the initiation fracture experiments are summarized in Figure 1. Although the data are statistically sparse, clear trends can be deduced from the initiation results.

For each of the microstructures, the initiation toughness increases by a small but discernible amount with increasing loading rate and the rate sensitivity appears to depend on the microstructure. For the microstructures with 40% and 12% primary alpha, the initiation toughness increases by about 12% when the loading rate is increased from 2×10^{-1} to 10^6 $MPa\sqrt{m}/s^{-1}$. For the microstructure with 0% primary alpha, the increase is only about 8%. At a given loading rate, the microstructural

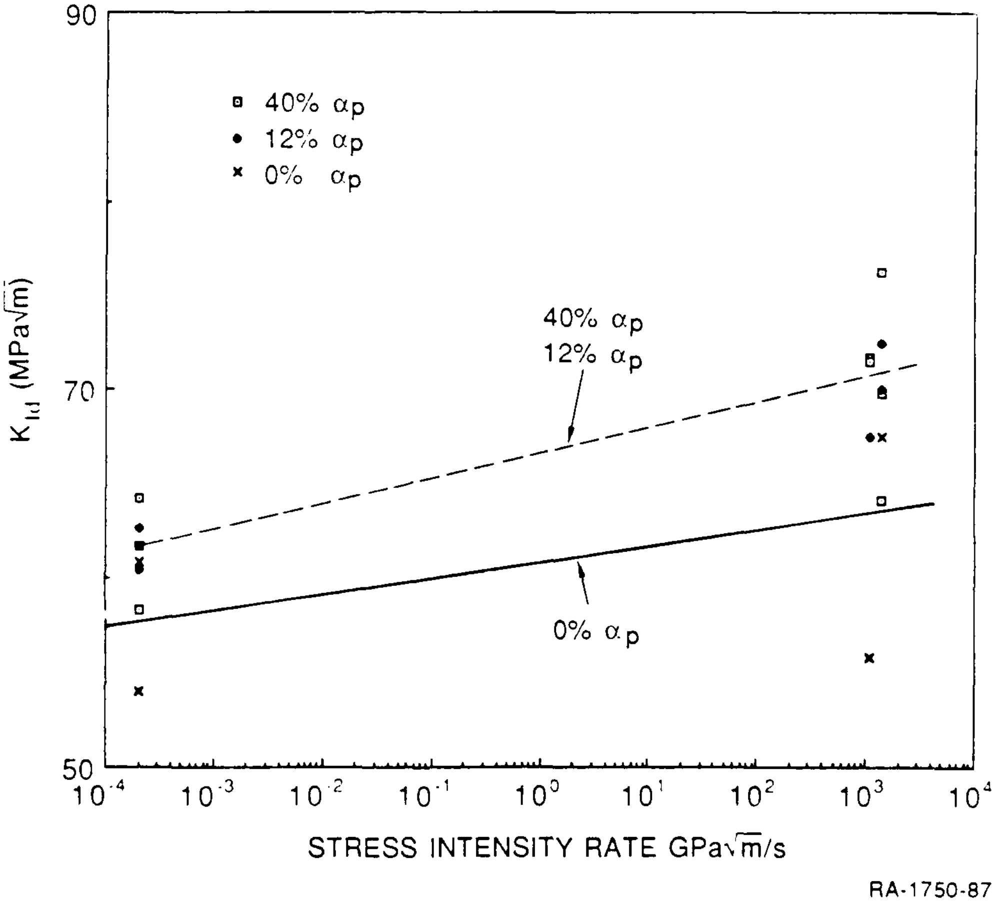


Figure 1. Initiation toughness of Ti -10 V -2 Fe -3 Al as a function of loading rate and percent primary alpha.

condition also affects the initiation toughness in a discernible way. Whereas the two microstructures containing primary alpha have approximately the same initiation toughness, the initiation toughness of the 0% primary alpha microstructure is 6% to 10% lower.

We are currently performing fractographic and metallographic investigations to seek microstructural reasons for these crack initiation fracture results.

Crack Propagation Fracture Experiments

We performed dynamic crack propagation experiments for several initiation conditions, again using the one-point bend test. However, to achieve the stress intensities necessary to propagate the crack through the specimen, we had to add ballast plates at both ends of the specimen, a method developed in our previous AFOSR-sponsored program.

We instrumented each specimen with a strain gage mounted near the initial crack tip and photographed the crack propagation with a high-speed framing camera. We also measured the impact load history to use as input for numerical simulations of the experiments. Finally, in selected cases we instrumented the specimen with additional strain gages mounted along the anticipated crack path to obtain another estimate of the crack velocity and to measure strain histories in the crack plane region.

We varied the crack initiation conditions by varying the impact velocity or, for a given impact velocity, by changing the root radius of the initial notch. We used fatigue-precracked specimens and specimens with notch root radii of 0.125 mm or 0.2 mm. Table 1 summarizes the experimental conditions for the 13 crack propagation fracture experiments we performed. Initial crack speeds between 50 and 400 m/s were achieved in the experiments.

A preliminary analysis of the crack propagation experiments indicates that microstructural condition significantly influences crack propagation behavior in Ti-10V-2Fe-3Al. This result is illustrated in Figure 2, which compares the crack propagation histories for the three microstructures and

Table 1

EXPERIMENTAL CONDITIONS FOR CRACK PROPAGATION FRACTURE EXPERIMENTS

Specimen	Microstructure (% primary alpha)	Notch Radius (mm)	Impact Velocity (m/s)	Initiation Stress Intensity (MPa $\sqrt{m}$)	Initial Crack Speed (m/s)
IBTI	40	Fatigue Crack	13.9	96	160
1BT2	40	Fatigue Crack	13.8	88	N/A
1BT3	40	0.25	14.0	104	N/A
1BT4	40	0.25	9.8	105	63
1BT5	40	0.25	9.9	79	71
1BT6	40	0.38	14.0	187	340
2BT1	12	Fatigue Crack	14.0	70	N/A
2BT2	12	0.25	14.2	70	180
2BT3	12	0.38	14.2	105	260
3BT1	0	Fatigue Crack	14.2	55	140
3BT2	0	0.25	14.0	70	180
3BT3	0	0.38	14.2	93	410
1IR1	40	Fatigue Crack	17.9	61	140

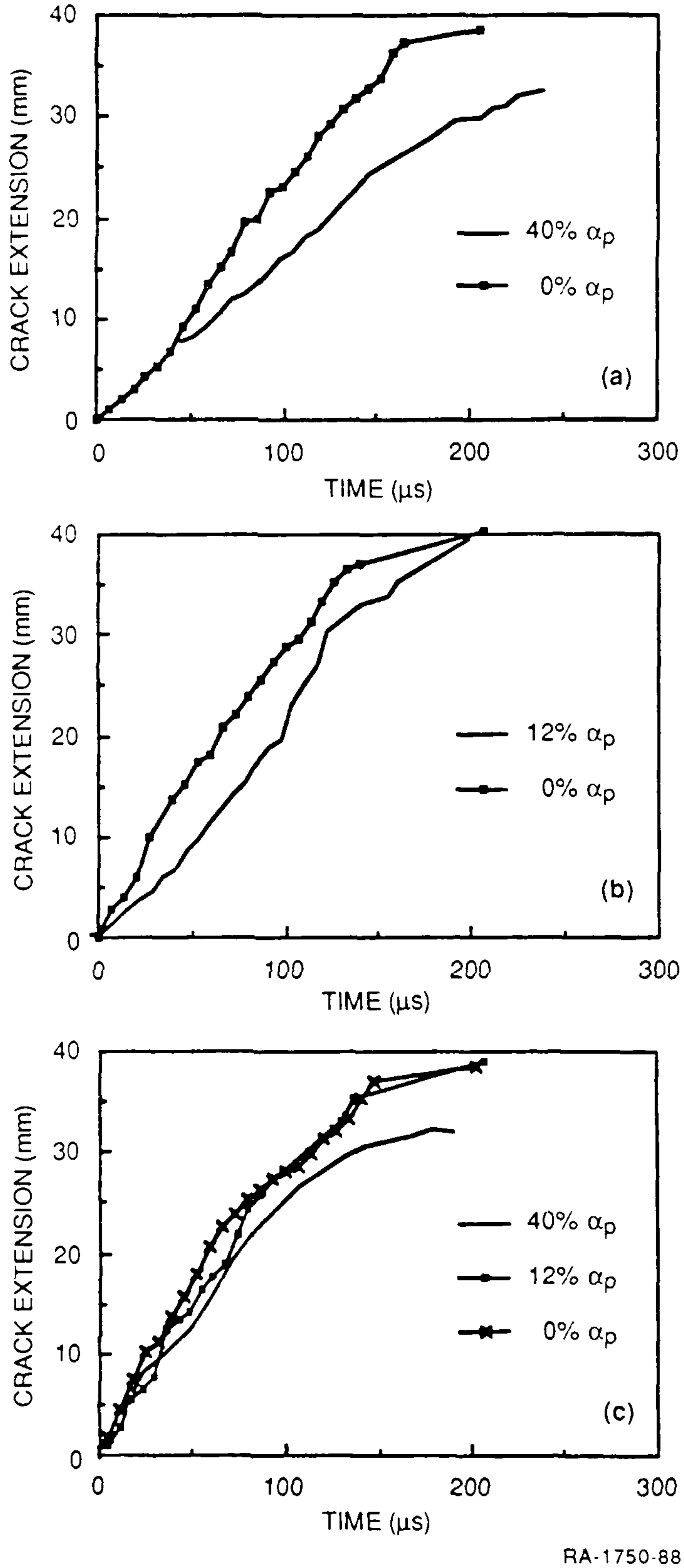


Figure 2. Crack velocity in impact loaded Ti -10 V -2 Fe -3 Al specimens as a function of notch root radius.
(a) Fatigue-precracked; (b) 0.25 mm notch radius; (c) 0.4 mm notch radius.

for three different notch root radii. The impact velocity was the same in all cases (~14 m/s). Figure 2(a) does not show the results for the 12% primary alpha microstructure and Figure 2(b) does not show the results for the 40% primary alpha microstructure because we could not obtain high-speed photographs of the propagating crack for the corresponding experiments. Figure 2 demonstrates that for given experimental conditions, crack speeds are significantly higher in the microstructure without primary alpha than in the other two microstructures. On the other hand, the 12% and the 40% primary alpha microstructures appear to have comparable crack propagation behaviors.

From the data in Figure 2 we conclude that the microstructure with 0% primary alpha has a significantly lower propagation fracture toughness than the two other microstructures. This conclusion is supported by the observation that hardly any shear lips were formed in the specimens with 0% primary alpha, whereas 1- to 2-mm-wide shear lips developed during crack propagation in the other two microstructures. Since the shear lip width is roughly proportional to the square of the toughness, the difference in the shear lip width demonstrates the difference in propagation toughness.

We are presently performing numerical simulations of the experiments to obtain a quantitative evaluation of the differences in propagation fracture toughness of the three microstructures.

Fractographic Observations and Fracture Surface Topography Analysis (FRASTA)

For each of the three microstructures, we examined with the scanning electron microscope (SEM) the fracture surfaces of one specimen tested at quasi-static rate (0.2 MPa$\sqrt{m}$/s) and one specimen tested at dynamic rate (1.4 x 10^6 MPa$\sqrt{m}$/s). We began the FRASTA analysis of two specimens tested at the quasi-static rate, one specimen of the 40% primary alpha microstructure and one specimen of the 0% primary alpha microstructure.

Qualitative evaluations of the SEM results show that, for a given loading rate, the fracture mode shifts from predominantly transgranular to predominantly intergranular as the primary alpha content is decreased. We also observed that for a given microstructure, the fracture surface roughness decreases with increasing loading rate. At quasi-static loading rates, the fracture surfaces have a disjointed appearance, with large cracks perpendicular to the main crack plane. We observed no such cracks in the fracture surfaces of specimens tested dynamically.

The detailed SEM observations revealed a variety of fractographic features on the surfaces depending on the microstructure and the loading rate. We identified two size scales of the fracture surface features. The larger size scale is on the order of many tens of micrometers. Fractographic features of this size scale include grains or grain fragments, grain facets resulting from grain boundary separations or from transgranular fracture, cracks perpendicular to the main crack plane, and large stretch and slip regions.

The smaller size scale is on the order of many micrometers. Fractographic features of this size consist predominantly of microvoids and often cover the surfaces of features of the larger size scale. The morphology, size, and density of the microvoids vary with the microstructural condition and with the loading rate.

From these observations we conclude that the mechanisms responsible for the formation of the various fractographic features are complex. Inhomogeneous slip is one of the dominant mechanisms by which the three studied microstructures fail. Slip, transgranular flat fractures, and grain boundary separation are responsible for the formation of large cracks and tubular cavities. These large defects are then linked by microvoid nucleation and growth.

We will further clarify the dependence of the microfailure processes on microstructure and loading rate by studying metallographic cross sections perpendicular to the fracture surfaces and by FRASTA.

Future Work

We are currently performing finite element simulations of the dynamic crack propagation experiments. The crack position history and the impact force history recorded during the experiments provide the input for these simulations, in which we calculate the stress intensity at the propagating crack tip. These simulations will allow us to establish how propagation toughness varies with crack speed (within the range of crack speeds achieved in the experiments) and with microstructure. The simulations will also provide verification of our experimental procedure to determine the stress intensity history with strain gages.

In the coming months, we will perform FRASTA on dynamically loaded fracture specimens and will attempt to refine the procedure to resolve the finer details of the fracturing processes. We will compare the crack opening displacement values obtained with FRASTA with the initiation toughness values and establish if correlations can be established as a function of microstructure and loading rate. We will define a measure of the fracture surface roughness based on the topographic data and compare the fracture surface roughness values and the propagation toughness values.

To complement the fractographic observations, we will prepare metallographic cross sections of several fracture specimens to examine subsurface damage, which we believe plays a significant role in the fracturing of this alloy. We will also identify which microstructural features contribute to the failure process and how these features affect the fracture surface morphology.

VI PUBLICATIONS AND PRESENTATIONS

Papers prepared or published and presentations made during the previous AFOSR-sponsored program are listed below.

Publications

J. F. Kalthoff and D. A. Shockey, "Instability of Cracks Under Impulse Loads," J. Appl. Phys. 48, 984-993 (March 1977).

D. A. Shockey, J. F. Kalthoff, H. Homma, and D. C. Erlich, "Criterion for Crack Instability Under Short Pulse Loads," Advances in Fracture Research, D. Francois et al., Eds. (Oxford and Pergamon Press, New York, 1980), pp. 415-423.

D. A. Shockey, J. F. Kalthoff, and D. C. Erlich, "Evaluation of Dynamic Crack Instability Criteria," Int. J. Fract. Mech. 22, 217-229 (1983).

D. A. Shockey, J. F. Kalthoff, W. Klemm, and S. Winkler, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," Exp. Mech. 23, 140-145 (1983).

H. Homma, D. A. Shockey, and Y. Murayama, "Response of Cracks in Structural Materials to Short Pulse Loads," J. Mech. Phys. Solids 31, 261-279 (1983).

D. A. Shockey, J. F. Kalthoff, H. Homma, and D. C. Erlich, "Response of Cracks to Short Pulse Loads," Proceedings of the Workshop on Dynamic Fracture, W. G. Knauss, Ed., held at the California Institute of Technology. Pasadena, CA, under sponsorship of the National Science Foundation and the Army Research Office, Feb. 17-18, 1983. pp. 57-71.

J. H. Giovanola, "Investigation and Application of the One-Point-Bend Impact Test," in Fracture Mechanics: Seventeenth Volume, ASTM STP 905, J. G. Underwood, R. Chait, C. W. Smith, D. P. Wilhelm, W. A. Andrews, and J. Newman, Eds. (American Society for Testing and Materials, Philadelphia, 1986), pp. 307-328.

J. H. Giovanola, "The One-Point-Bend Test," in ASM Metals Handbook, 9th Edition, Volume 8, Mechanical Testing (American Society for Metals, Metals Park, OH, 1985) pp. 271-275.

D. A. Shockey, "Short-Pulse-Duration Tests," in ASM Metals Handbook, 9th Edition, Volume 8, Mechanical Testing (American Society for Metals, Metals Park, OH 1985), pp. 282-284.

D. A. Shockey, J. F. Kalthoff, H. Homma, and D. C. Erlich, "Short Pulse Fracture Mechanics," in Dynamic Fracture, The Albert S. Kobayashi Anniversary Volume of the International Journal of Fracture, M. F. Kanninen and S. N. Atluri, Eds (Pergamon Press, New York, 1986), pp. 311-319.

J. H. Giovanola, "Crack Initiation and Extension in Steel for Short Loading Times," in the Proceedings of DYMAT '85, International Conference on Mechanical and Physical Behavior of Materials under Dynamic Loading, Paris, September 2-5 (1985) (Les Editions de Physique, France, 1985), pp. C5-171 through C5-178.

Publications in Preparation

J. H. Giovanola, R. W. Klopp, J. LeMonds, D. A. Shockey, and A. T. Werner, "The Influence of Microstructure and Loading Rate on the Fracture Behavior of Ti-10V-2Fe-3Al," to be submitted to Metallurgical Transactions.

J. H. Giovanola, R. W. Klopp, J. LeMonds, and D. A. Shockey, "Crack Propagation Studies Using the One-Point-Bend Experiment," to be submitted to Engineering Fracture Mechanics.

Presentations

D. C. Erlich and D. A. Shockey, "Instability Conditions for Cracks Under Short-Duration Pulse Loads," Topical Conference on Shock Waves in Condensed Matter, Meeting of the American Physical Society, Washington State University, Pullman, WA, June 11-13, 1979.

D. A. Shockey, "Instability Conditions for Cracks Loaded by Short Stress Pulses," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, December 12, 1979.

D. A. Shockey, "Dynamic Crack Instability," Institut CERAC, Ecublens, Switzerland, May 19, 1980.

D. A. Shockey, "Dynamic Crack Instability," Institut fu Werkstoffmechanik, Freiburg, Germany, May 21, 1980.

D. A. Shockey, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, June 1980.

D. A. Shockey, "Criterion for Crack Instability Under Short Pulse Loads," Fifth International Conference on Fracture (ICF5), Cannes, France, March 29-April 3, 1981.

D. A. Shockey, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," 18th Annual Meeting of the Society for Engineering Science, Inc., Brown University, Providence, RI, September 2-4, 1981.

D. A. Shockey, "Short Pulse Fracture Mechanics," Seminar for the Department of Applied Mechanics, Stanford University, Stanford, CA, March 3, 1983.

D. A. Shockey, "Short Pulse Fracture Mechanics," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, April 11, 1983.

J. H. Giovanola, "Mechanics of Fracture Under Pulse Loads; Minimum Time Theory Revisited," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, April 1984.

J. H. Giovanola, "Material Failures at High Strain Rates," two lectures given at the Department of Materials Science and Engineering of Stanford University, May 1984.

J. H. Giovanola, "Material Failures at High Strain Rate," Materials Science and Engineering Graduate Seminar, University of California Berkeley, November 1984.

J. H. Giovanola, "Investigation and Analysis of the One-Point-Bend Impact Test," presented at the ASTM Seventeenth National Symposium on Fracture Mechanics, Albany, NY, August 7-9, 1984.

D. A. Shockey, D. R. Curran, and L. Seaman, "Fracture Under Impact Loads," presented at the International Conference on Dynamic Fracture Mechanics, San Antonio, November 7-9, 1984.

J. H. Giovanola,"The One-Point-Bend Test: Experiment and Analysis,"Poulter Laboratory Seminar, SRI International, Menlo Park, CA, March 1985.

D. A. Shockey, J. F. Kalthoff, H. Homma, and J. H. Giovanola, "Recent Results in Short Pulse Fracture Mechanics," presented at the SEM Spring Meeting, Las Vegas, June 1985.

J. H. Giovanola, "Crack Initiation and Extension in Steel for Short Loading Times," presented at DYMAT International Conference on Mechanical and Physical Behavior of Materials under Dynamic Loading, Paris, September 2-5 (1985).

J. H. Giovanola: "Fracture of High Loading Rates," presented at the University of California Berkeley Short Course, Fracture and Fatigue: Approaches for Analysis and Control of Failure, June 1986.

List of Personnel

Dr. D. A. Shockey, Principal Investigator
Dr. J. H. Giovanola, Principal Investigator
Dr. R. W. Klopp
Dr. J. LeMonds
Dr. T. Duerig, consultant

END
DATE
FILMED
DTIC
6-88